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Bubbly-ice densification in ice sheets: I. Theory

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Abstract

Dry snow on the surface of polar ice ice sheets is first densified and metamorphosed to produce firn. Bubbly ice is the next stage of the transformation process which takes place below the depth of pore closure. This stage extends to the transition zone where, due to high pressures and low temperatures, air trapped in bubbles and ice begins to form the mixed air clathrate hydrates, while the gas phase progressively disappears. Here we develop a model of bubbly-ice rheology and ice-sheet dynamics taking into account glacier-ice compressibility. The interaction between hydrostatic compression of air bubbles, deviatoric (uniaxial) compressive deformation of the ice matrix and global deformations of the glacier body is considered. The ice-matrix pressure and the absolute-load pressure are distinguished. Similarity theory and scale analysis are used to examine the resultant mathematical model of bubbly-ice densification. The initial rate of bubble compression in ice sheets appears to be relatively high, so that the pressure (density) relaxation process takes place only 150-200 m in depth (below pore close-off) to reach its asymptotic phase, wherein the minimal drop between bubble and ice pressures is governed by the rate of loading (ice accumulation). This makes it possible to consider densification under stationary (present-day) conditions of ice formation as a special case of primary interest. The computational tests performed with the model indicate that both ice-porosity and bubble-pressure profiles in ice sheets are sensitive to variations of the rheological parameters of pure ice. However, only the bubble-pressure profile distinguishes between the rheological properties at low and high stresses. The porosity profile at the asymptotic phase is mostly determined by the air content in the ice. In the companion paper (Lipenkov and others, 1997), we apply the model to experimental data from polar ice cores and deduce, through an inverse procedure, the rheological properties of pure ice as well as the mean air content in Holocene and glacial ice sediments at Vostok Station (Antarctica).